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Solar radiation and temperature as predictor variables for dry matter intake in beef steers

Mustapha Yusuf[1], Kendall C. Swanson[1], Lauren L. Hulsman Hanna[1], Ronald Degges[2] and Marc L. Bauer[1*]

[1]Department of Animal Science, North Dakota State University, Fargo, ND, United States,
[2]Department of Statistics, North Dakota State University, Fargo, ND, United States

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EDITED BY
Todd Riley Callaway,
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REVIEWED BY
Michael Gonda,
South Dakota State University,
United States
Tryon Wickersham,
Texas A&M University, United States
Blake Wilson,
Oklahoma State University,
United States

*CORRESPONDENCE
Marc L. Bauer
marc.bauer@ndsu.edu

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Solar radiation may be an important weather variable that has not been included in previous dry matter intake (DMI) prediction models. Solar radiation affects the overall effective ambient temperature, which in turn contributes to the net gain of heat in an animal's body. This experiment examined ambient temperature and solar radiation with DMI in beef steers. Data from 790 beef steers collected between 2011 and 2018 using an Insentec feeding system was used. Daily data was condensed into weekly averages (n = 13,895 steer-weeks). The variables considered for this study were DMI (2.50 to 23.60 kg/d), body weight (197 to 796 kg), calculated dietary energy density (NE_m; 0.79 to 2.97 Mcal/kg), ambient temperature (-23.73 to 21.40°C), two-week lag of ambient temperature (-20.73 to 23.56°C), monthly lag of ambient temperature (-17.95 to 22.74°C), solar radiation (30.8 to 297.1 W/m^2), two-week lag of solar radiation (34.6 to 272 W/m^2) and monthly lag of solar radiation (43.7 to 256.6 W/m^2). Residuals of DMI fitting week of the year (fixed) and experiment (random) were used to generate scatter plots with other explanatory variables to identify if non-linear relationships existed. Body weight and NE_m had both linear and quadratic relationships with DMI, while the relationship with DMI for other variables was linear. The MIXED procedure of SAS with Toeplitz variance-covariance structure was used to determine the final model of DMI. After accounting for body weight and NE_m in the model, two-week lag of ambient temperature and monthly lag of solar radiation interacted together (P = 0.0001), and this accounted for 0.7790 (R^2) variation in DMI and improved the model fit. Therefore, these two variables and their interactions should be considered in DMI prediction equations of beef steers.

KEYWORDS

steers, dry matter intake, solar radiation, temperature, prediction, cattle

Introduction

It has been well established that the thermal environment has significant influence on livestock species (NRC, 1981). Animals compensate for changes in their thermal environment by either adjusting the amount of energy they consume, improving their method of heat dissipation or altering their metabolism. Thornton et al. (2009) reported that when animals do not acclimatize to a sudden change in weather, the result is reduction in production, or even death. The change in the environment due to climate change poses a risk to livestock production, and this necessitates accounting for more of the environmental (weather) variables that influence dry matter intake. This will enable producers to provide for their livestock more accurately with the amount of nutrients and energy to reduce their vulnerability to normal and extreme weather conditions.

Thermoregulation in cattle is dependent on the breed, physiological class, age, and diet. Thermoregulation is achieved by the interaction of extrinsic environment with the intrinsic environment, which results in a response for the maintenance of homeostasis. The response could be in the form of lowering metabolism, vasoconstriction, or increasing the quantity of hairs (Nakamura and Morrison, 2008). Collier et al. (2019) summarized the effect of varying thermal conditions on feed intake in Holstein cows in a controlled environment. They observed a decrease in feed intake as the thermal environment increased from a temperature humidity index (THI) of 57 to 72 (cool to hot). They also reported that an array of environmental factors such as ambient temperature, solar radiation, relative humidity and windspeed are known to have either direct or indirect effects on livestock. However, to the best of our knowledge, DMI estimation models for beef cattle do not account for the effect that solar radiation may have on DMI. In addition, the current DMI models available may not fit the northern Great Plains of North America well, where temperatures can be as low as -30°C in the winter (Block et al., 2001). Therefore, improving these models may be beneficial. Our objective was to examine how much variation in DMI is accounted for by ambient temperature and solar radiation.

Materials and methods

Data collection

Data used for this experiment were collected from the Beef Cattle Research Complex (BCRC) of North Dakota State University, Fargo, North Dakota located at latitude 46.9027853 degrees North and longitude -96.8418183 degrees West. An Insentec feeding system (RIC feeding system; Hokofarm Group, Marknesse, The Netherlands), which records the amount of feed intake, number of visits, time of visit and meals for each animal, was used for the data collection. The data used were from 10 experiments that were conducted between 2011 to 2018 (Table 1). The Insectec system does a good job of reducing feed waste, for this study, feed disappearance from the bunk is assumed to be the intake by the animals.

Weather data

Data for weather variables were obtained from the North Dakota Agricultural Weather Network (NDAWN) station, which is 2.33 km from the BCRC (NDAWN, 2021). Each NDAWN station is assumed by NDAWN to adequately represent all weather conditions, except rainfall, in a 32 km radius. For this study, daily summaries of each weather variable were averaged for each week and these weekly averages were used in the analysis as described below.

Weather variables modeled for this study included: ambient temperature, the average air temperature of the surrounding environment for a 24-hour period from midnight to midnight (°C); solar radiation, sum of all hourly totals of incident solar radiation energy for a 24-hour period from midnight to midnight. Total incident solar radiation flux density is measured in Watts/m^2 at approximately 2 m above the soil surface with a pyranometer, and two-week lag and monthly lag of each weather variable was also considered. Two-week lag is the average of the previous two week's weather variable while monthly lag is the average of the previous month's weather variable.

Non-weather variables

The non-weather variables considered for this experiment include weekly average of daily dry matter intake (DMI) in kg, weekly average body weight (BW) in kg, dietary concentration of net energy for maintenance (NE_m) Mcal/kg of DM, experiment, and the week of the year. Week of the year ranged from week 1 to 22 and week 38 to 52.

Data management

The daily feed intake data were averaged into weekly averages to reduce the day-to-day fluctuation. Dry matter analysis (AOAC, 2010) of the diet was conducted on samples collected weekly and used, along with as-fed feed intake, to calculate DMI consumed by each animal. Weekly BW for each animal was calculated from BW data collected monthly by using simple linear regression. Daily ambient temperature and solar radiation were averaged per week to align with weekly DMI Dietary NE_m was calculated by using the equation of Lofgreen and Garrett (1968) and Zinn and Chen (1998) using initial BW, final BW, average daily gain (ADG) and average DMI. Table 2 shows the descriptive statistics of the variables used for this study.

TABLE 1 Experiments used in this study.

Month, year (week of the year)		Steers, n[1]	Steer-week observations, n[1]	Breed[2]	Publication
Start	End				
Nov. 2011 (wk 45)	Jan. 2012 (wk 4)	67	804	AN, SM, and SH	Islas et al., 2014
Nov. 2012 (wk 46)	Feb. 2013 (wk 5)	94	1,120	AN, SM, and SH	Prezotto et al., 2017
March 2012 (wk 10)	June 2012 (wk 22)	63	819	AN, SM, and SH	Swanson et al., 2014
Feb. 2013 (wk 6)	June 2013 (wk 22)	66	1,098	AN, SM, and SH	Swanson, et al., 2017a
Sep. 2013 (wk 38)	Feb 2014 (wk 5)	113	2,260	AN-crossbred	Swanson et al., 2018
March 2014 (wk 11)	June 2014 (wk 22)	44	527	AN, SM, and SH	Swanson et al., 2017a
Jan. 2014 (wk 4)	June 2014 (wk 22)	81	1,339	AN, SM, and SH	Rodenhuis et al., 2017
Dec. 2015 (wk 51)	May 2016 (wk 18)	61	1,211	AN, SM, and SH	Knutson et al., 2020
Nov. 2016 (wk 45)	May 2017 (wk 20)	134	3,432	AN, SM, and SH	Sitorski et al., 2019
Nov. 2017 (wk 46)	April 2018 (wk 15)	67	1,285	AN and SM	Trotta et al., 2019

[1]n, number.
[2]AN, Angus; SM, Simmental; SH, Shorthorn.

Statistical analysis

Data were analyzed using the MIXED procedure of SAS 9.4 software (SAS Institute Inc. 2015) and within-individual relationship due to repeated measures per steer was accounted for using the Toeplitz covariance structure. Raw DMI was initially fit to output residuals adjusted for week of the year (fixed) and experiment (random). DMI residuals were then investigated for linear correlations and scatter plots with weight, NE_m, and weather variables using CORR procedure of SAS. Raw DMI was then fit with a base model, which included linear and quadratic effects of BW and NE_m, week of the year (fixed), and experiment (random) effects. The base model was expanded in a stepwise addition of weather variables as fixed covariates using maximum likelihood (ML) to compare fit. Each version of each weather variable (no-lag, two-week lag, monthly lag) were fit independently of other versions so that each weather variable was present in the model only once. Akaike information criterion (AIC) and Bayesian information criterion (BIC) values were used to assess model fit during the stepwise process. Once the final model was determined, parameter estimates were generated using the restricted maximum likelihood estimation (REML) procedure and solution statement. Coefficient of determination (R^2) for each model was calculated using the glmmQPL function in R (v 4.2.1, R Core Team, 2022).

Results

Correlation between BW, NE_m and residuals of DMI

The correlation between BW and NE_m, and residuals of DMI, adjusted for week of the year (fixed) and experiment (random), confirmed that linear and quadratic relationships exist after examining the trend of the scatter plots and testing the linear

TABLE 2 Descriptive statistics of variables across the period of experiment.

Variable[1]	Mean	Minimum	Maximum	SD[2]	SE[3]
BW, kg	474	197	796	99.04	0.84
DMI, kg/d	10.69	2.50	23.60	2.76	0.02
NE_m, Mcal/kg of DM	2.01	0.79	2.97	0.30	0.00
Ambient temperature, °C					
No lag	-2.01	-23.73	21.40	10.45	0.09
Two-week lag	-2.19	-20.73	23.56	9.58	0.08
Monthly lag	-2.24	-17.95	22.74	9.05	0.08
Solar radiation, W/m^2					
No lag	112.5	30.8	297.1	64.00	0.54
Two-week lag	107.0	34.6	272.0	58.57	0.50
Monthly lag	104.2	43.7	256.6	54.31	0.46

[1] Variable with 13,895 observations, BW, body weight; DMI, dry matter intake; NE_m, net energy for maintenance.
[2]SD, Standard deviation.
[3]SE, Standard error.

and quadratic effects of BW and NE_m in the model. The correlation coefficients for the relationships for BW and NE_m with DMI were 0.2312 (P < 0.0001; Figure 1.) and -0.073 (P< 0.0001; Figure 2.), respectively. Therefore, both the linear and quadratic effect of BW and NE_m were retained in the model (Table 3).

Base model, ambient temperature, and solar radiation

Table 4 provides model summary statistics when fitting each weather variable independently of each other to the base model. Inclusion of all three forms (no-lag, two-week lag, and monthly lag) in a single model was not possible due to multicollinearity. All three ambient temperature variables were significant sources of variation, with the two-week lag providing the best model fit statistics (Table 4). Model parameters when including the two-week lag regressor are provided in Table 5.

For solar radiation, only monthly lag of solar radiation was significant and improved model fit statistics compared to the base model (Table 4). Model parameters, when including the monthly lag regressor of solar radiation are provided in Table 6. When the main effect of two-week lag of ambient temperature and monthly lag of solar radiation were included in the model, only two-week lag of ambient temperature was significant (P < 0.005) in the model (Table 7). Although, the main effect of monthly lag of solar radiation was not significant when considered with two-week lag of ambient temperature, monthly lag of solar radiation was significant when included in the model alone. This prompted examination of an interaction between these two variables.

When the interaction between two-week lag of solar radiation and monthly lag of solar radiation was included in the model while retaining the main effects of each, the fit improved and indicated a significant interaction (Table 8). The BIC values were reduced by 5 points indicating an improvement in model fit relative to the previous model that had no interaction between ambient temperature and solar radiation included. The reason the main effects were insignificant could be because of a cancellation effect that the main effects and the interactions had on each other. When only the interaction between two-week lag of ambient temperature and monthly lag of solar radiation were added to the base model, the interaction was highly significant (P = 0.0001), and the AIC and BIC values were lower indicating the model was improved and has a better model fit (Table 9; Figure 3). Since the interaction between two-week lag of ambient temperature and monthly lag of solar radiation gave a better model fit, the interaction was left in the model while their main effects were removed. AIC, BIC, and R^2 values for the models are shown (Table 10). It is important to note that there is no agreed way of calculating R^2 in mixed models of SAS. Therefore, R statistical software was implemented using the method described by Nakagawa et al. (2017). Caution should be taken when interpreting the R^2 values because it is an index that is likely to interpret only a few aspects of model fit to the data and should not be used to determine the quality of the model but rather should be used along with the AIC and BIC values (Nakagawa and Schielzeth, 2013; Nakagawa et al., 2017).

Discussion

Body weight as a predictor for DMI has long been reported (Lehmann, 1941; Kruger and Schulze, 1956; Conrad et al, 1964; Baile and Forbes, 1974). It is necessary to account for BW in our model so that the contribution of BW the variation in DMI by

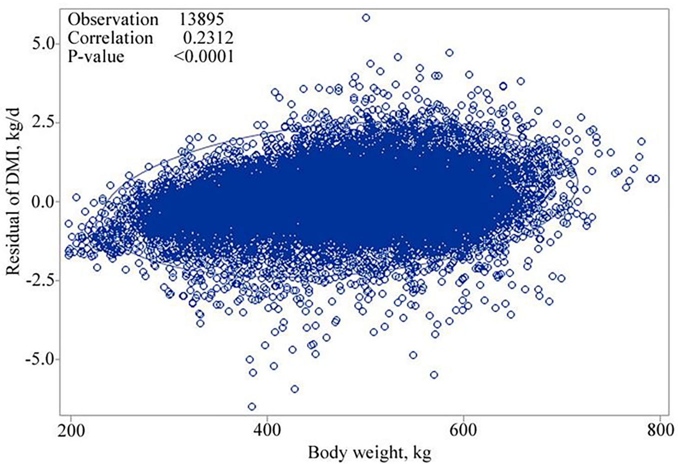

FIGURE 1
Scatter plot showing the relationship of residuals of dry matter intake (DMI) against body weight, kg.

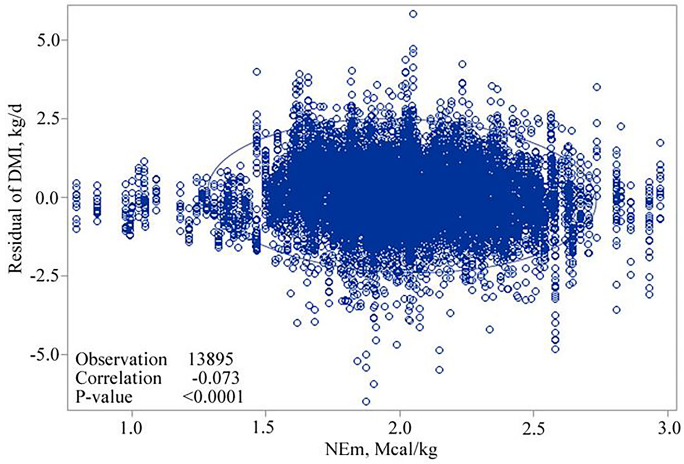

FIGURE 2
Scatter plot showing the relationship of residuals of dry matter intake (DMI) against net energy for maintenance (NE_m, Mcal/kg of DM).

other variables can be examined more accurately. Generally, our data starts with younger, lighter calves in the fall and winter, and ends with older, heavier calves in late winter, spring, and early summer, depending on the study. When analyzed, BW of steers are distributed across season, but the effect of age, BW, or a combination may still not be completely accounted for in our base model. Dietary energy density (Mcal of NE_m/kg of feed) has also been reported by many authors as a major determinant of DMI in ruminants (Crampton et al, 1957; Blaxter, 1961; Baumgardt, 1970).

Previous temperature is thought to influence basal metabolism, thereby indirectly affecting DMI (NRC, 1981). This is supported by the work of Fox and Tylutki (1998), who recommended that the average over a month should be used in prediction models to remove the day-to-day variation because temperature changes slowly from season to season. In this study, data was collected during the colder months with average weekly temperature ranging from -2 to 24°C and average weekly solar radiation from 30 to 300 W/m^2; therefore, this model may not accurately represent regions with warmer temperatures and/or different solar radiation patterns. Environmental factors affecting DMI has been previously reported (NRC, 1981). Hill and Wall (2017) reported that at high temperatures, DMI typically decreases. Other factors such as growth rate and BW also affect DMI. Hill and Wall (2017) reported that thermal stress (either high or low temperature) might be better handled by efficient cattle compared to less efficient cattle. Efficient cattle are better at directing feed to growth and have been reported to have lower rectal temperatures and produce less metabolic heat (Basarab et al., 2003). NRC (1981) recommended a thermoneutral temperature range of 15 to 25°C for beef cattle. For cold weather conditions, DMI is often thought to increase. However, an apparent relationship between ambient temperature and DMI does not exist as reported by NRC (1981) because ambient temperature is most likely influenced by other variables. For example, Mader et al. (2010) reported that the strength of

TABLE 3 Variables in the base model using restricted maximum likelihood estimation method (REML).

Variable[1]	Estimates	SE[2]	F-value	P-value
Intercept	-6.20×10^{0}	1.25×10^{0}	——	0.0008
Week of the year			34.62	0.0001
Body weight, kg				
Linear	4.75×10^{-2}	2.27×10^{-3}	437.85	0.0001
Quadratic	-3.00×10^{-5}	2.27×10^{-6}	184.47	0.0001
Dietary NE_m, Mcal/kg of DM				
Linear	3.69×10^{0}	9.70×10^{-1}	14.55	0.0001
Quadratic	-1.31×10^{0}	2.43×10^{-1}	29.12	0.0001

[1] Variables with 13,895 observations.
[2]SE, Standard error.

TABLE 4 AIC, BIC, F and P values of each weather variable considered when added to the base model individually using maximum likelihood estimation method (ML).

Variable[1]	F-value	P-value	AIC[2]	BIC[3]
Base model	——	——	45,067	45,088
Ambient temperature, °C				
No lag	28.82	0.0001	45,041	45,063
Two-week lag	55.52	0.0001	45,017	45,038
Monthly lag	27.52	0.0001	45,044	45,065
Solar radiation, W/m^2				
No lag	3.67	0.0553	45,065	45,087
Two-week lag	0.32	0.5703	45,068	45,090
Monthly lag	10.95	0.0009	45,058	45,080

[1]Variables with 13,895 observations.
[2]AIC, Akaike information criterion.
[3]BIC, Bayesian information.

TABLE 5 Base model with two-week lag of ambient temperature.

Variable[1]	Estimates	SE[2]	F-value	P-value
Intercept	-6.42×10^{0}	1.24×10^{0}	——	0.0006
Week of the year	——	——	35.23	< 0.0001
Body weight, kg				
Linear	4.76×10^{-2}	2.27×10^{-3}	441.09	< 0.0001
Quadratic	-3.00×10^{-5}	2.27×10^{-6}	186.94	< 0.0001
Dietary NE_m, Mcal/kg				
Linear	3.70×10^{0}	9.68×10^{-1}	14.58	0.0001
Quadratic	-1.31×10^{0}	2.43×10^{-1}	29.15	< 0.0001
Two-week lag of ambient temperature, °C	-2.17×10^{-2}	2.91×10^{-2}	55.52	< 0.0001

[1]Variables with 13,895 observations.
[2]SE, Standard error.

TABLE 6 Base model with monthly lag of solar radiation.

Variable[1]	Estimates	SE[2]	F-value	P-value
Intercept	-5.91×10^{0}	1.24×10^{0}	——	0.0010
Week of the year	——	——	33.95	< 0.0001
Body weight, kg				
Linear	4.70×10^{-2}	2.27×10^{-3}	428.53	< 0.0001
Quadratic	-3.00×10^{-5}	2.27×10^{-6}	179.66	< 0.0001
Dietary NE_m, Mcal/kg				
Linear	3.70×10^{0}	9.65×10^{-1}	14.71	0.0001
Quadratic	-1.31×10^{0}	2.43×10^{-1}	29.40	< 0.0001
Monthly lag of solar radiation, W/m^2	-3.20×10^{-3}	9.67×10^{-4}	10.95	0.0009

[1]Variables with 13,895 observations.
[2]SE, Standard error.

TABLE 7 Base model with two-week lag of ambient temperature and monthly lag of solar radiation.

Variable[1]	Estimates	SE[2]	F-value	P-value
Intercept	-6.31×10^{0}	1.24×10^{0}	——	0.0007
Week of the year	——	——	34.92	< 0.0001
Body weight, kg				
Linear	4.74×10^{-2}	2.27×10^{-3}	434.66	< 0.0001
Quadratic	-3.00×10^{-5}	2.28×10^{-6}	183.97	< 0.0001
Dietary NE_m, Mcal/kg				
Linear	3.70×10^{0}	9.67×10^{-1}	14.60	0.0001
Quadratic	-1.31×10^{0}	2.43×10^{-1}	29.20	< 0.0001
Two-week lag of ambient temperature, °C	-2.07×10^{-2}	3.06×10^{-3}	45.63	< 0.0001
Monthly lag of solar radiation, W/m^2	-1.05×10^{-3}	1.01×10^{-3}	1.07	0.3012

[1]Variables with 13,895 observations.
[2]SE, Standard error.

relationship between ambient temperature and DMI might be questioned because DMI is influenced by cattle type, body condition, management, and other environmental factors. In our study, we accounted for the variation that could be explained by BW, dietary energy density, individual differences in animals and time of the year. All possible variations that may exist from the animal and the environment which are known to affect DMI were accounted for in the base model. However, there could be other unknown variables that affect DMI that were not accounted for, such as solar radiation and the interaction between ambient temperature and solar radiation.

Solar radiation has been reported to have an influence on ambient temperature and heat loss from animals (Brosh et al., 1998). The sun angle changes daily and seasonally, which influences the thermal balance of the animal because exposed surface area and insulation are affected differentially (Keren and Olson, 2006). A perpendicularly standing animal to the sun's ray will absorb more short-wave radiation than one standing parallel to the sun (Clapperton et al., 1965). Factors such as sky conditions, ground cover and the shape and orientation of the animal's body also determine the amount of solar radiation absorbed (Keren, 2005). Prediction models used in the past did not examine the lag of solar radiation nor did they consider solar radiation separately, rather it was considered with other weather variables using an index named current effective temperature index (CETI) which accounts for temperature, humidity, wind speed and sunlight hours (Tedeschi and Fox, 2016). Mader et al. (2010) developed a comprehensive climate index (CCI) using ambient temperature while adjusting for relative humidity, wind speed and solar radiation. This type of indices do not explain the interaction of solar radiation or its lag with temperature on DMI.

The better model fit we observed in this study between the interaction between solar radiation and ambient temperature indicates that solar radiation is important and could better explain the variation in DMI than just temperature alone. Others (Bakken, 1981; Mader et al., 2010; Tedeschi and Fox, 2016) have considered ambient temperature and some weather variables together, combining them into an index. This shows that

TABLE 8 Base model, two-week lag of ambient temperature and monthly lag of solar radiation and their interaction.

Variable[1]	Estimates	SE[2]	F-value	P-value
Intercept	-6.32×10^{0}	1.25×10^{0}	——	0.0007
Week of the year			32.92	< 0.0001
Body weight, kg				
Linear	4.75×10^{-2}	2.28×10^{-3}	435.37	< 0.0001
Quadratic	-3.00×10^{-5}	2.28×10^{-6}	183.98	< 0.0001
Dietary NE_m, Mcal/kg				
Linear	3.69×10^{0}	9.68×10^{-1}	14.56	0.0001
Quadratic	-1.31×10^{0}	2.43×10^{-1}	29.13	< 0.0001
Two-week lag of ambient temperature, °C	-6.91×10^{-3}	6.00×10^{-3}	1.33	0.2494
Monthly lag of solar radiation, W/m^2	3.08×10^{-4}	1.14×10^{-3}	0.07	0.7867
Two-week lag of ambient temperature × monthly lag of solar radiation, °C × W/m^2	-1.40×10^{-4}	5.20×10^{-5}	7.18	0.0074

[1]Variables with 13,895 observations.
[2]SE, Standard error.

TABLE 9 Base model and interaction between two-week lag of ambient temperature and monthly lag of solar radiation using restricted maximum likelihood estimation method (final model).

Variable[1]	Estimates	SE[2]	F-value	P-value
Intercept	-6.23×10^{0}	1.26×10^{-0}	——	0.0008
Week of the year			33.71	< 0.0001
Body weight, kg				
Linear	4.74×10^{-2}	2.27×10^{-3}	434.78	< 0.0001
Quadratic	-3.00×10^{-5}	2.27×10^{-6}	182.89	< 0.0001
Dietary NE_m, Mcal/kg				
Linear	3.69×10^{0}	9.67×10^{-1}	14.47	0.0001
Quadratic	-1.31×10^{0}	2.43×10^{-1}	28.99	< 0.0001
Two-week lag of ambient temperature × monthly lag of solar radiation, °C × W/m²	-1.80×10^{-4}	2.30×10^{-5}	61.92	< 0.0001

[1]Variables with 13,895 observations.
[2]SE, Standard error.

multiple weather variables interact together to affect DMI suggesting that combining weather variables into an index should be discouraged. It is important to note that, although the main effect of week of the year was accounted in this study, there might be an interaction between week of the year and temperature or solar radiation. We did not try to account for this interaction in this study to avoid complexity in the models.

National Academies of Science, Engineering, and Medicine (NASEM, 2016) reported that solar radiation accentuates the effect of temperature. In our model, solar radiation accentuated the effect that low and high temperature had on DMI. Interestingly, in Figure 3, it can be observed that, with increasing temperature and reduction in solar radiation, DMI increased. This could be attributed to the interaction between temperature and solar radiation and how they influence each other. This could suggest that on sunny days with high temperature, DMI decreases but on sunny days with extremely low temperature, DMI increases. In extreme cold temperatures, the NE_m requirement of cattle increases linearly and, therefore, the animal needs to increase energy intake from feed to meet the requirement for increased heat production and maintenance of homeostasis. There is a dearth of information on the effect of solar radiation on animals in extremely cold weather conditions. Most reported studies examined the effect of solar radiation on animals in warm to hot weather conditions (Mader et al., 2006; Mader at al., 2010; Melton et al, 2018; Lees et al., 2019). Studies that examined the effect of cold weather conditions on animals (Siple and Passel, 1945) did not examine the effect of solar radiation on DMI. Siple and Passel (1945) developed a windchill index (WCI), relating ambient temperature (Ta) and wind speed (WS) to the time for freezing water for cold conditions. Mader et al. (2006) developed adjustments to the THI based on

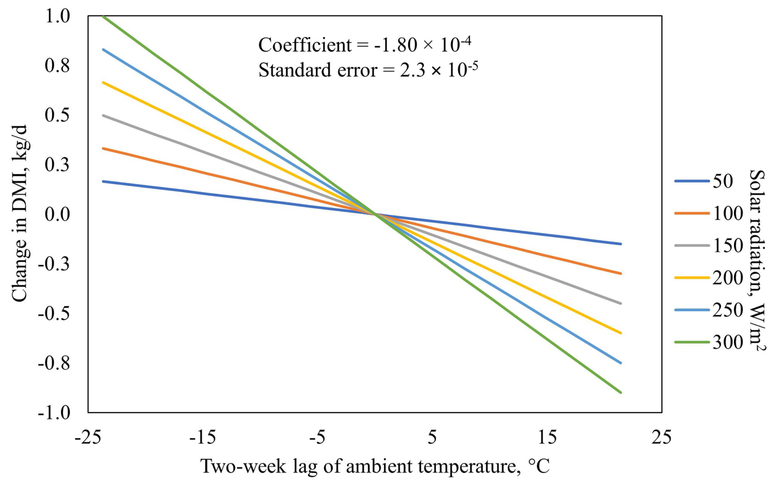

FIGURE 3
The final model interaction between two-week lag of ambient temperature and monthly lag of solar radiation and their influence on dry matter intake (DMI). F-value = 61.92. *P*-value < 0.0001.

TABLE 10 AIC, BIC, and R^2 (coefficient of determination) values of various models examining solar radiation as a predictor variable for DMI in beef steers to summarize the model fit in each stepwise process.

Variable[1]	AIC[2]	BIC[3]	R^2
Base model only (Restricted Maximum likelihood estimation method)	45,151*	45,160*	——
Base model only (Maximum Likelihood estimation method)	45,067†	45,088†	0.7708
Two-week lag of ambient temperature + base model	45,017†	45,038†	0.7744
Monthly lag of solar radiation + base model	45,058†	45,080†	0.7761
Two-week lag of ambient temperature + Monthly lag of solar radiation + base model	45,018†	45,040†	0.7755
Two-week lag of ambient temperature + Monthly lag of solar radiation and their interaction + base model	45,013†	45,035†	0.7790
Interaction between two-week lag of ambient temperature and monthly lag of solar radiation + base model[4]	45,011†	45,032†	0.7790
Best model using restricted maximum likelihood estimation method	45,113*	45,121*	——

[1] Variable with 13,895 observations. Units are °C for temperature and W/m^2 for solar radiation.
[2]AIC, Akaike information criterion.
[3]BIC, Bayesian information criterion.
[4] Best model.
†Maximum likelihood estimation method was used.
*Restricted maximum likelihood estimation method was used.

panting scores and measures of wind speed and solar radiation but only two studies were conducted in cold weather conditions in the data they examined. Olson (1938) examined the effect of sunlight on dairy cattle that were exposed to sunlight or without sunlight and fed the same amount of feed. The no-sunlight group had better growth than the sunlight group because the sunlight group were housed outside and maintained under cold winter conditions. This corroborates the effect of extreme cold weather on energy requirements and growth. If the intake of the animal does not increase to meet the energy demand for heat production, growth performance is compromised. On the other hand, under high ambient temperatures, livestock are expected to have decreased DMI to reduce their metabolic heat production. Mader et al. (2010) reported that solar radiation and ambient temperature have a linear relationship, which is similar with what we observed in this study. Heat input from metabolic heat production and solar radiation, and heat output from evaporative and non-evaporative avenues are the factors that determine body temperature in cattle (Brosh et al., 1998). As temperature decreased to below the lower critical temperature, the animal becomes cold stressed, and the maintenance energy requirement increases. Although it is often assumed that DMI increases with decreasing temperature in cold weather, Donald (1988) reported that animals under severe cold stress tend to have reduced intake. However, in this study, DMI increased with increasing solar radiation and reduction in temperature. This may be because increases in solar radiation lessen the negative effect of the cold stress on the animal resulting in an increase DMI. Olson and Wallander (2002) reported that during extreme cold weather, cattle spent more time standing to maximize heat gain from solar radiation instead of lying down. However, our final model indicates that DMI increased with increasing solar radiation and decreasing temperature, whereas DMI decreased with increasing solar radiation and increasing temperature. DMI changed less when solar radiation was minimal. This may be because increases in solar radiation lessens the negative effect of cold stress or enhances the negative effect of hotter ambient temperatures on the animal resulting in changes in DMI.

Solar radiation is known to influence thermal balance of ruminants. Study by Sevi et al. (2001) examined the effect of solar radiation on Comisana ewes. They reported that solar radiation and the interaction between solar radiation and feeding time had significant effect on rectal temperatures. This indicates that solar radiation influences thermal balance, energy metabolism and could be attributed to the change in DMI at different intensities of solar radiation. Solar radiation has been reported to directly affect the surface that an animal has contact with as well as the temperature of the animal, especially in dark-hided cattle (Mader et al., 2006). Kennedy et al. (1986) reported that in cold weather, ruminal motility and digesta passage increases, which could be contributing factors to the observed increases in DMI. Sunshine hours and day length both contribute to solar radiation reaching an animal directly or indirectly (absorbed by surrounding surfaces and the ground). Dahl et al. (2000) observed a positive relationship between milk production and day length which could be because of reduced melatonin production with increasing photoperiod. The influence of day length and temperature on performance of Swedish red and white bulls fed ad libitum concentrates or ad libitum forage and concentrates was reported to observe an increase in DMI as day length increased (Mossberg and Jonsson, 1996). This is similar to the result in this study where increased solar radiation in cold weather was observed to increase DMI but caused a reduced DMI in warmer temperatures.

It was reported by NASEM (2016) that other adverse weather conditions can increase the effects of ambient temperature. However, the response to temperature varies between animals (Young, 1981). The observed increase in DMI as two-week lag of temperature decreases, and monthly lag of solar radiation increases, could also be attributed to the long-term effect of solar radiation on melatonin. Light inhibits melatonin secretion by inhibiting the production of N-acetyltransferase, the primary enzyme for melatonin synthesis (Hickman et al., 1999). Melatonin slows metabolism, increases fat deposition and decreases feed intake and, ultimately, productivity of animals. With more light and solar radiation, we speculate that this caused a reduction in melatonin secretion over time, therefore, contributing to the observed increase in feed intake. However, more research is needed on the relationships between solar radiation, melatonin secretion, DMI, and growth.

Conclusion

To summarize, our results showed that variation in DMI was better explained by having the interaction between two-week lag of ambient temperature and monthly lag of solar radiation in the prediction model as opposed to ambient temperature alone. This indicates that solar radiation could be a good predictor and explain some variation in DMI occurring because of thermal effects. Furthermore, using a model similar to the model developed in this study may be a better alternative than using THI or CCI as an index combining effects of individual weather variables.

Implications

Changes in and the interaction between solar radiation and temperature were associated with changes in DMI. We suggest that these variables may be important and should be considered in DMI prediction equations. Dry matter intake changes in response to adverse weather conditions. Dry matter intake is influenced by several factors and how cattle respond to changes in DMI is highly variable among individuals. Understanding the variables that influence DMI will help in increasing the accuracy of DMI prediction models, which will in turn assist producers and feedlot managers better manage daily feed delivery and feed inventories. Further research to examine how other weather variables such as windspeed and dewpoint interact with temperature and solar radiation to influence DMI and ADG is needed.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the animal study because all data had been collected previously. All previous studies were reviewed and approved by the North Dakota State University Animal Care and Use Committee.

Author contributions

MY compiled the data, analyzed the data, and wrote the manuscript. KS helped with raw data collection, formatting, and manuscript review. LHH contributed to the analysis of the data and manuscript review. RD contributed to the analysis of the data. MB helped with raw data collection, formatting, data analysis, manuscript preparation, review, and submission.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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